



# Taguchi approach for co-gasification optimization of torrefied biomass and coal



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## HIGHLIGHTS

- Taguchi method is employed to optimize co-gasification.
- Torrefied biomass (eucalyptus) and coal are co-gasified in an entrained flow gasifier.
- Cold gas efficiency is adopted as the index of the performance of co-gasification.
- O/F ratio is the most important factor in determining co-gasification.
- Optimized cold gas efficiency and carbon conversion are 80.99% and 94.51%, respectively.

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## ABSTRACT

This study employs the Taguchi method to approach the optimum co-gasification operation of torrefied biomass (eucalyptus) and coal in an entrained flow gasifier. The cold gas efficiency is adopted as the performance index of co-gasification. The influences of six parameters, namely, the biomass blending ratio, oxygen-to-fuel mass ratio (O/F ratio), biomass torrefaction temperature, gasification pressure, steam-to-fuel mass ratio (S/F ratio), and inlet temperature of the carrier gas, on the performance of co-gasification are considered. The analysis of the signal-to-noise ratio suggests that the O/F ratio is the most important factor in determining the performance and the appropriate O/F ratio is 0.7. The performance is also significantly affected by biomass along with torrefaction, where a torrefaction temperature of 300 °C is sufficient to upgrade eucalyptus. According to the recommended operating conditions, the values of cold gas efficiency and carbon conversion at the optimum co-gasification are 80.99% and 94.51%, respectively.

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## 1. Introduction

Coal is an important fuel for power generation, and is also an essential raw material for ironmaking in the iron and steel industry (Du et al., 2010). Boilers and blast furnaces are the most commonly employed facilities to consume coal through combustion; however, this results in large amounts of air pollutants and greenhouse gases being emitted into the atmosphere. Currently, the remarkable development of gasification is a promising technology to consume coal in a clean way, which has been dubbed clean coal technology (Irfan et al., 2011), allowing carbon capture and storage to be achieved in the process. Another advantage of gasification is that a variety of fuels, such as biomass, solid wastes, slurry, and petroleum coke, can be employed as feedstock.

In addition to low sulfur and ash content, biomass has a much shorter life cycle (Taba et al., 2012) when compared to fossil fuels. Therefore, using biomass as a fuel is an effective countermeasure to

mitigate the exhaustion of fossil fuels and reduce emissions of air pollutants and carbon dioxide while simultaneously providing heat and power. However, biomass is characterized by low bulk energy density, hydrophobicity, easier decay in storage, and high grinding energy requirement (Aigner et al., 2011). Consequently, the application of biomass in industry is a challenge. The co-gasification of coal and biomass offers several advantages over individual coal or biomass gasification because it links two different fuels in the gasifier. Co-gasification enables biomass to be used as a feasible fuel with higher efficiency in large scale gasifiers. Moreover, the alkali species in biomass possess the catalytic effect which can improve coal gasification (Habibi et al., 2013). Therefore, biomass feedstocks may provide an inexpensive source of gasification catalysts to co-convert fossil fuels and lower the energy requirements of co-gasification.

The co-gasification of biomass and coal and its optimization have been investigated (Fermoso et al., 2010); however, its reaction phenomena are more complicated than the individual gasification of either coal or biomass, and the co-gasification process is influenced by many factors stemming from the blend of two different fuels. As such, there is a need to systemically determine the

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optimum operation of co-gasification. A number of methods can be used for process optimization, and of them, the Taguchi method is one of the optimization routes that minimizes the number of tests and identifies the important parameters in a system (Taguchi, 1990), thereby allowing the reduction of costs in the course of seeking optimum operation. The advantages of this approach are that numerous factors can be simultaneously optimized and much quantitative information can be extracted from small-scale experiments (Chou et al., 2009). The Taguchi method is versatile, and has been employed in various fields including aerospace and environmental engineering (Singaravelu et al., 2009; Zolfaghari et al., 2011).

In applying the Taguchi method in energy research, Zheng et al. (2012) optimized oil recovery from oil sludge. They found that the predicted optimum biosurfactant formula of 2.0 g/L rhamnolipid, pH 12.0, 10 g/L NaCl, and 5.0 g/L nbutanol were validated by a washing experiment that yielded an oil recovery of 74.55%. Liu et al. (2012) studied the effects of seven parameters on corn stover saccharification with concentrated sulfuric acid through a Taguchi experimental design. Their results indicated that the concentration of sulfuric acid and the temperature of solubilization significantly affected corn stover decomposition as well as glucose and xylose recovery. Adu-Gyamfi et al. (2012) evaluated the effects of different parameters on methane production in an anaerobic digestion system using the Taguchi method, and the optimization improved methane productivity by 153%. Mohan and Reddy (2013) also used the Taguchi method to analyze the influence and specific function of eight important factors on bioplastics production. Their results suggested that the microenvironment influenced bioplastics production substantially, followed by pH and glucose concentration.

Torrefaction, a mild pyrolysis process at temperatures of 200–300 °C, is receiving a great deal of attention for biomass pre-treatment because it is able to efficiently improve the properties of biomass (Arias et al., 2008; Chen et al., 2011). For example, torrefaction ensures the low affinity of water in biomass (Felfri et al., 2005), whereby the pretreated materials can be stored for extended periods of time. The energy density of biomass is intensified via torrefaction (Deng et al., 2009; Chen and Kuo, 2011) so that the torrefied biomass is closer to coal, leading to a higher utilization efficiency of biomass. In recent studies (Coughert et al., 2009; Chen et al., 2013), it has been reported that torrefied biomass can enhance the efficiency of biomass gasification in a significant way.

In reviewing past literature, it was found that a systematic study for the co-gasification optimization of coal and biomass, especially for torrefied biomass, by means of the Taguchi method remains absent. The Taguchi method is of great use in identifying the influences of operating factors on the performance of co-gasification and establishing their relationships. Therefore, the present study aims to determine the optimum operating conditions for the co-gasification of coal and torrefied biomass through the application of numerical simulations and the Taguchi method.

## 2. Numerical method

### 2.1. Geometry of gasifier and governing equations

A dry feed and pressurized entrained flow gasifier with a capacity of two metric tons per day (Shen et al., 2012) was employed as the co-gasification reactor of biomass and coal. The height and diameter of the gasifier are 5151.2 and 270.3 mm, respectively. Three inlets, comprising a center inlet, an inner ring, and an outer ring, were constructed at the top of the reactor. Fuels along with carrier gas are sent into the gasifier from the center inlet; oxygen was transported via the inner ring, and steam was fed through the outer ring. Detailed configurations of the gasifier are sketched in Fig. 1.

The phenomena of co-gasification involve fluid dynamics, heat and mass transfers, and chemical reactions. To approach the phenomena and make the simulation more tractable, the following assumptions are employed:

- (1) The flow field is steady, axisymmetric, and incompressible because of the cylindrical gasifier adopted and the low-Mach number flow in the reactor involved.
- (2) Compared to coal or biomass combustion, the temperature of gasification is relative low and the high-temperature zone is small because of insufficient oxygen supplied. Therefore, thermal radiation in the gasifier is ignored. The body force of the fluid is ignored as well.
- (3) The concentrations of air pollutants, such as  $\text{NH}_3$ ,  $\text{HCN}$ ,  $\text{H}_2\text{S}$ ,  $\text{CS}_2$ , and  $\text{COS}$ , in the product gas are low when compared to those of  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and  $\text{CH}_4$  (Vicente et al., 2003), the formation of the air pollutants is thus neglected.
- (4) The wall of the gasifier is adiabatic by postulating the perfect refractory installed in the gasifier.

On account of the assumption of axisymmetric flow, two-dimensional, steady-state, and time-averaged Navier–Stokes, energy, and species equations are solved. The standard  $k$ – $\varepsilon$  turbulence model is also adopted. In regard to fuel particle motion, it is modeled by a Lagrangian approach called the discrete phase model (DPM). In this model, the trajectories of fuel particles are tracked when they move through the continuous phase of the fluid (Silaen and Wang, 2010). The interaction between the discrete phase and the continuous phase is also taken into account by treating the heat and mass losses of the particles as the source terms in the governing equations. The detailed governing equations, standard  $k$ – $\varepsilon$  turbulence model, and particle motion can be found elsewhere (Chen et al., 2013).

### 2.2. Chemical reactions

The reactions include the devolatilization of coal or biomass, the combustion of volatiles, and the gasification of char. When fuel particles are devolatilized and followed by gasification, the

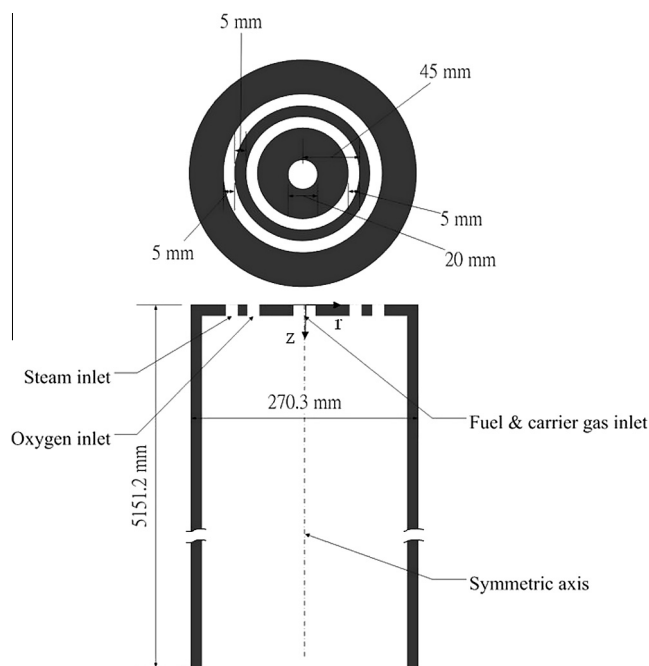
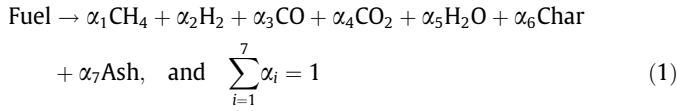


Fig. 1. Schematic of the top view and side view of entrained-flow gasifier.

produced gases, char, and ash from the gasification process can be described by the following equilibrium equation (Chen et al., 2012):



A two-step devolatilization model (Du and Chen, 2006) is utilized to predict the devolatilization process, which dominates the reaction in the initial injection period, and is expressed as follows:



The reaction kinetics are expressed by:

$$\frac{dV}{dt} = (k_l Y_l + k_h Y_h) \text{Fuel} \quad (4)$$

$$k_l = A_l \exp(-E_{a,l}/RT_p) \quad (5)$$

$$k_h = A_h \exp(-E_{a,h}/RT_p) \quad (6)$$

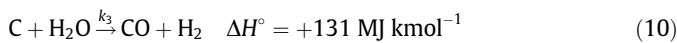
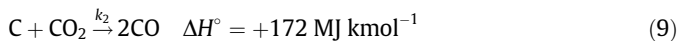
In the above equations,  $Y$  is the stoichiometric coefficient,  $V$  the mass fraction of volatiles,  $k$  the reaction rate constant,  $A$  the pre-exponential factor,  $T_p$  the fuel particle temperature, and  $E_a$  the reaction activation energy. The two-step model is controlled by the values of  $Y_l$ ,  $k_l$ ,  $Y_h$ ,  $k_h$ ,  $E_l$ , and  $E_h$ . Specifically, when the temperature is low, the devolatilization process is dominated by Eq. (2); conversely, it is governed by Eq. (3) if the temperature is high. The values of  $Y_l$ ,  $k_l$ ,  $Y_h$ ,  $k_h$ ,  $E_l$ , and  $E_h$  have been reported and the model has been validated by Du and Chen (2006).

Following the devolatilization processes, the reaction of volatiles is featured by the following equation:

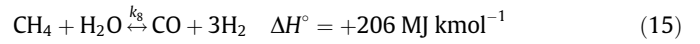
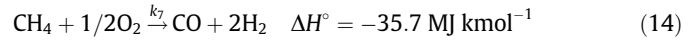
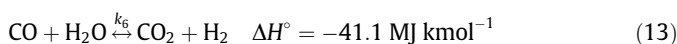
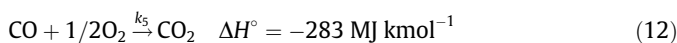
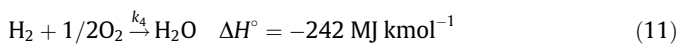


The values of the coefficients  $a$ ,  $b$ , and  $c$ , are calculated in accordance with the elemental analysis of the feedstock. Accordingly, the reaction process of biomass is different from that of coal as a consequence of different percentages of elements in the fuels.

When char is produced from coal or biomass devolatilization, CO and H<sub>2</sub> are generated from char gasification. Char gasification can be described by the following equations (Roberts and Harris, 2000):



where  $\Delta H^\circ$  is the reaction heat at the standard state (i.e. 298 K and 1 atm). Further, the gas-phase chemical reactions include (Jones and Lindstedt, 1988):



### 2.3. Taguchi method

The performance of the Taguchi method is measured by the deviation of a characteristic from its target value and a loss function derived from statistics (Liao and Kao, 2010). The approach of the loss function works whether the objective is maximization, minimization, or reaching a certain target. The loss function takes the following basic quadratic form:

$$L(y) = K(y - T)^2 \quad (16)$$

where the value of  $L$  is the loss,  $K$  a constant which depends on the magnitude of the characteristic,  $T$  the target response, and  $y$  the measured response.

The advantage of the Taguchi method is its ease of use and emphasis on reducing variability to give a more economical production. The focus of the Taguchi method is to make the process or product insensitive to those sources of variation. In the Taguchi method, the signal-to-noise ratio (S/N ratio) is employed to analyze the quality characteristics of product or process parameters. The Taguchi method defines three different forms of S/N ratio, including the nominal-the-better (NB), the larger-the-better (LB), and the smaller-the-better (SB). Regardless of the category of performance characteristic, a larger S/N ratio corresponds to a better characteristic performance. The cold gas efficiency (CGE) is an important index in accounting for the performance of gasification. The index is determined from the concentrations of H<sub>2</sub>, CO, and CH<sub>4</sub> in the product gas and is defined as (Jones and Lindstedt, 1988):

$$\text{CGE (\%)} = \frac{\dot{m}_{\text{out}}(y_{\text{H}_2} \text{HHV}_{\text{H}_2} + y_{\text{CO}} \text{HHV}_{\text{CO}} + y_{\text{CH}_4} \text{HHV}_{\text{CH}_4})}{\dot{m}_{\text{in, fuel}} \text{HHV}_{\text{fuel}}} \times 100 \quad (17)$$

where  $\dot{m}$ ,  $y$ , and HHV are the mass flow rate, the mass fraction, and the higher heating value, respectively. The higher the CGE (optimum value = 100), the better the gasification performance. CGE is thus selected as the evaluation criteria for the S/N ratio, and the S/N ratio of the NB is adopted for this study. The S/N ratio is calculated in terms of the loss function using the following formula (Taguchi, 1990):

$$\text{S/N} = -10 \log[(y - T)^2] \quad (18)$$

where  $T$  is the highest value of CGE and its value = 100, while  $y$  is the predicted amount of CGE at each gasification simulation run. Carbon conversion (CC) is another important index to evaluate the consumption or conversion of feedstock, and is expressed as:

$$\text{CC (\%)} = \left( 1 - \frac{\dot{m}_{\text{out}}(y_{\text{CO}_2} \frac{12}{44} + y_{\text{CO}} \frac{12}{28} + y_{\text{CH}_4} \frac{12}{16})}{\dot{m}_{\text{in, fuel}} y_c} \right) \times 100 \quad (19)$$

### 2.4. Numerical method

Numerical simulations were carried out by means of the commercial CFD code ANSYS FLUENT V12 to consider the co-gasification phenomena, while the SIMPLE algorithm was used to adjust pressure and gas velocity to satisfy gas continuity. The second-order upwind scheme was employed to calculate the convection and diffusion fluxes. To reduce the numerical truncation error, the computational domain was constructed using an orthogonal grid system. Four different grid systems, consisting of 8800, 17,600,

35,200, and 70,400 mesh numbers, were tested and compared with each other to outline a proper grid system for predicting the chemical reactions. In the test, only air (300 K) with a flow rate of  $0.025 \text{ kg s}^{-1}$  was sent into the reactor. The pressure in the gasifier was fixed at 2 MPa and the wall temperature was 1700 K. Corresponding to the four grid systems, the mean temperatures at the exit of the gasifier were 1579, 1556, 1524, and 1526 K, respectively. The difference in temperature between the third (35,200) and the fourth grid systems (70,400) is slight, implying that the third grid system satisfies the requirement of grid independence. Consequently, the mesh number of 35,200 was adopted for the numerical predictions. In a previous study (Chen et al., 2012), the chemical kinetics of gasification were successfully established and the numerical predictions were in good agreement with the experimental data.

### 2.5. Operating conditions and parameters

Blends of biomass and coal were selected as feedstocks, and oxygen and steam were used as oxidants. The coal was a high-volatile bituminous coal (Chen, 2007), while the biomass was raw or torrefied eucalyptus (Lu et al., 2012). The pretreated eucalyptus was torrefied at temperatures of 250, 275, 300, and  $325^\circ\text{C}$  for 1 h. The properties of the fuels, such as proximate, elemental, and calorific analyses are tabulated in Table 1. The mass flow rate of the fuel blend was  $0.023 \text{ kg s}^{-1}$ , and air, with a mass flow rate of  $0.025 \text{ kg s}^{-1}$ , was employed as the carrier gas to aid in transporting fuel particles. The temperatures of steam and oxygen were 127 and  $27^\circ\text{C}$ , respectively. The sizes of the fuel particles were in the range of 44–250  $\mu\text{m}$ , with an average particle size of 103  $\mu\text{m}$ , as determined by the Rosin–Rammmler distribution function.

The influence of six parameters (or factors) on the performance of co-gasification was taken into account, namely the biomass blending ratio (BBR), oxygen-to-fuel mass ratio (O/F ratio), torrefaction temperature of biomass, gasification pressure, steam-to-fuel mass ratio (S/F ratio), and the inlet temperature of the carrier gas. Meanwhile, five levels for each parameter were selected. The values of the BBR, O/F ratio, torrefaction temperature, gasification pressure, S/F ratio, and inlet temperature were in the ranges of 5–25 wt%, 0.6–1.0, 250– $325^\circ\text{C}$ , 1–5 MPa, 0.03–0.15, and 27– $427^\circ\text{C}$ , respectively, to evaluate their impacts on the behavior of co-gasification. These factors and levels were selected based on a number of available studies (Chmielniak and Sciazko, 2003; Valero and Uson, 2006; Lapuerta et al., 2008; Cormos, 2012). Detailed values of the parameters in association with various levels are shown in Table 2.

## 3. Results and discussion

### 3.1. Parameter analysis

When six parameters (or factors) and five levels are adopted to find the optimum operation for the co-gasification of biomass and

coal, a total of  $(5^6) = 15,625$  runs are required if all cases are considered. The Taguchi method is characterized by its orthogonal array design, which simplifies the statistical design efforts to evaluate experimental data by combining the orthogonal array and the statistical analysis. Consequently, considerable time and resource are reduced when the important factors affecting operations are determined. An  $L_{25}(5^6)$  orthogonal array was used in this study and only 25 designed runs were required. The level combination of designed experiments in the  $L_{25}(5^6)$  orthogonal array, and the predicted values of CGE, CC, and S/N ratio are shown in Table 3. The maximum value of CGE is 80.23%, which occurs at Run 2, whereas the minimum value of 55.89% is found at Run 6. The difference between the maximum and minimum values is 24.34%, revealing that the performance of co-gasification is significantly affected by the combination of the factors and levels. The maximum and minimum values of CC are 96.21% and 56.11%, respectively, and were exhibited at Run 8 and 21. It is noteworthy that the CGE of Run 8 is 75.11%, which is lower than that of Run 2 by 5.12%. It follows that more  $\text{CO}_2$  rather than CO is produced in Run 8 when compared to Run 2, even though the former has a higher CC value than the latter. The maximum and minimum S/N ratios in the orthogonal array are 14.08 and 7.11, respectively. A similar trend in the CGE and S/N ratio is due to that the latter is determined in terms of the former.

According to the values of the S/N ratios obtained in Table 3, the profiles of the mean S/N ratios of the factors are plotted in Fig. 2a. The value of the mean S/N ratio at Factor A and Level 1 was calculated by the values of the S/N ratio from the five Level 1 values of Factor A shown in Table 3 (i.e. Runs 1–5). Alternatively, the value of the mean S/N ratio at Factor A and Level 2 was calculated from Runs 2, 7, 12, 17, and 22. The values of the mean S/N ratios of other factors and levels were calculated by a similar procedure. Based on the calculated mean S/N ratios, the effect value of each factor was determined by the maximum level value minus the minimum level value of the factor. The effect values of the six factors are shown in Fig. 2b. Physically, the higher the effect value, the more pronounced the influence of the corresponding factor on the performance of co-gasification. The values of the effect on Factors A–F are 0.91, 4.98, 1.64, 0.88, 0.56, and 0.85, respectively. Accordingly, the influence strength of the factors on co-gasification is ranked as: Factor B (O/F ratio) > Factor C (torrefaction temperature of biomass) > Factor A (biomass blending ratio) > Factor D (gasification pressure) > Factor F (inlet temperature) > Factor E (S/F ratio).

The effect value of Factor B (=4.98) is substantially higher than those of the others. It follows that the O/F ratio plays the most important role in determining the performance and value of CGE for co-gasification. The effect value of Factor C (=1.64) is also much higher than those of Factors A, D, E, and F. This reflects that biomass pretreated via torrefaction is able to improve the performance of co-gasification in a significant way. This result is

**Table 1**  
Proximate and elemental analyses of fuels.

| Fuel                                          | Eucalyptus |      |      |      |      | Coal |
|-----------------------------------------------|------------|------|------|------|------|------|
| Torrefaction temperature ( $^\circ\text{C}$ ) | Raw        | 250  | 275  | 300  | 325  | Raw  |
| <i>Proximate analysis (wt%, dry basis)</i>    |            |      |      |      |      |      |
| VM                                            | 81.1       | 75.0 | 70.9 | 55.6 | 41.7 | 34.9 |
| FC                                            | 18.9       | 24.7 | 28.9 | 44.1 | 57.9 | 58.9 |
| Ash                                           | 0          | 0.3  | 0.2  | 0.3  | 0.4  | 6.2  |
| <i>Elemental analysis (wt%, dry basis)</i>    |            |      |      |      |      |      |
| C                                             | 50.8       | 57.8 | 59.7 | 68.2 | 75.0 | 63.5 |
| H                                             | 5.1        | 4.9  | 4.7  | 4.2  | 3.6  | 4.7  |
| N                                             | 0          | 0    | 0    | 0    | 0    | 1.0  |
| O                                             | 44.1       | 37.0 | 35.4 | 27.3 | 21.0 | 24.6 |
| HHV ( $\text{MJ kg}^{-1}$ )                   | 20.6       | 21.5 | 23.9 | 26.0 | 26.0 | 26.2 |

**Table 2**

Factors, control parameter levels and control conditions of each case run.

| Factor | Control parameter             | Level |      |      |     |      |
|--------|-------------------------------|-------|------|------|-----|------|
|        |                               | 1     | 2    | 3    | 4   | 5    |
| A      | Biomass blending ratio (wt%)  | 5     | 10   | 15   | 20  | 25   |
| B      | O/F ratio                     | 0.6   | 0.7  | 0.8  | 0.9 | 1.0  |
| C      | Torrefaction temperature (°C) | –     | 250  | 275  | 300 | 325  |
| D      | Pressure (MPa)                | 1     | 2    | 3    | 4   | 5    |
| E      | S/F ratio                     | 0.03  | 0.05 | 0.07 | 0.1 | 0.15 |
| F      | Fuel inlet temperature (°C)   | 27    | 127  | 227  | 327 | 427  |

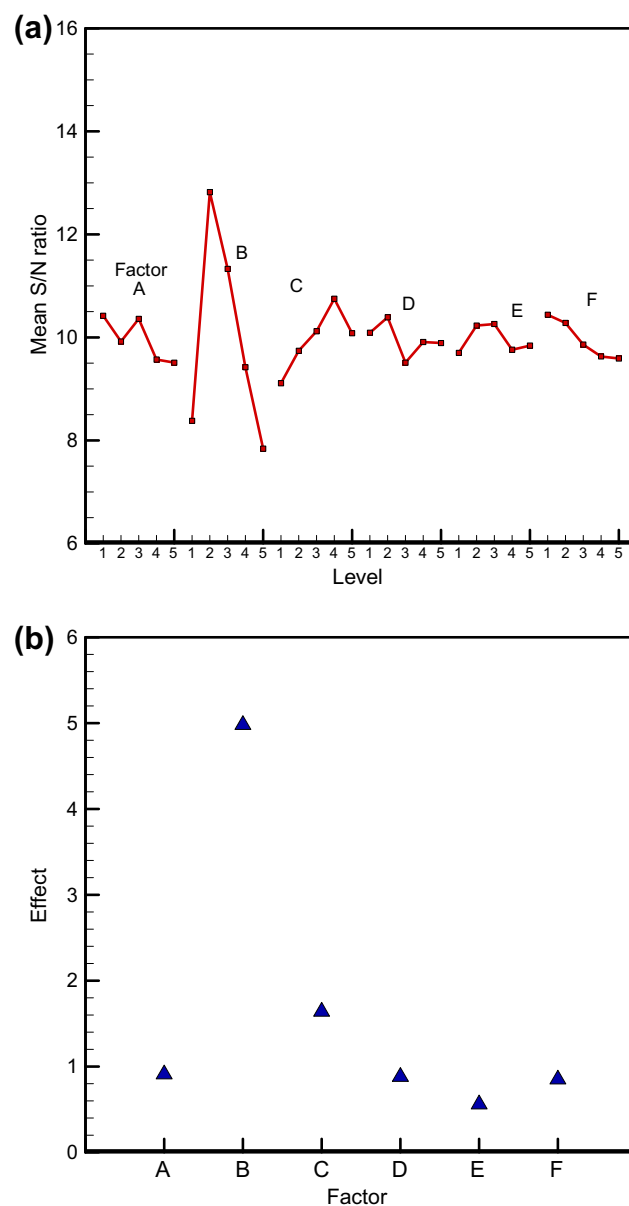
**Table 3**Level combination of designed experiments and results in  $L_{25} (5^6)$  orthogonal array.

| Run | Factor |   |   |   |   |   | CGE (%) | CC (%) | S/N   |
|-----|--------|---|---|---|---|---|---------|--------|-------|
|     | A      | B | C | D | E | F |         |        |       |
| 1   | 1      | 1 | 1 | 1 | 1 | 1 | 61.72   | 64.10  | 8.34  |
| 2   | 1      | 2 | 2 | 2 | 2 | 2 | 80.23   | 94.38  | 14.08 |
| 3   | 1      | 3 | 3 | 3 | 3 | 3 | 74.03   | 95.54  | 11.71 |
| 4   | 1      | 4 | 4 | 4 | 4 | 4 | 68.69   | 95.34  | 10.09 |
| 5   | 1      | 5 | 5 | 5 | 5 | 5 | 59.53   | 93.15  | 7.86  |
| 6   | 2      | 1 | 2 | 3 | 4 | 5 | 55.89   | 68.17  | 7.11  |
| 7   | 2      | 2 | 3 | 4 | 5 | 1 | 78.28   | 91.35  | 13.26 |
| 8   | 2      | 3 | 4 | 5 | 1 | 2 | 75.11   | 96.21  | 12.08 |
| 9   | 2      | 4 | 5 | 1 | 2 | 3 | 67.70   | 93.67  | 9.82  |
| 10  | 2      | 5 | 1 | 2 | 3 | 4 | 57.08   | 95.28  | 7.35  |
| 11  | 3      | 1 | 3 | 5 | 2 | 4 | 63.77   | 64.44  | 8.82  |
| 12  | 3      | 2 | 4 | 1 | 3 | 5 | 80.22   | 91.80  | 14.08 |
| 13  | 3      | 3 | 5 | 2 | 4 | 1 | 76.47   | 95.52  | 12.57 |
| 14  | 3      | 4 | 1 | 3 | 5 | 2 | 63.39   | 94.55  | 8.73  |
| 15  | 3      | 5 | 2 | 4 | 1 | 3 | 58.43   | 94.38  | 7.62  |
| 16  | 4      | 1 | 4 | 2 | 5 | 3 | 64.53   | 63.85  | 9.00  |
| 17  | 4      | 2 | 5 | 3 | 1 | 4 | 73.45   | 89.21  | 11.52 |
| 18  | 4      | 3 | 1 | 4 | 2 | 5 | 68.16   | 93.41  | 9.94  |
| 19  | 4      | 4 | 2 | 5 | 3 | 1 | 66.61   | 94.63  | 9.53  |
| 20  | 4      | 5 | 3 | 1 | 4 | 2 | 59.57   | 94.83  | 7.87  |
| 21  | 5      | 1 | 5 | 4 | 3 | 2 | 62.98   | 56.11  | 8.63  |
| 22  | 5      | 2 | 1 | 5 | 4 | 3 | 72.36   | 81.21  | 11.17 |
| 23  | 5      | 3 | 2 | 1 | 5 | 4 | 69.62   | 89.87  | 10.35 |
| 24  | 5      | 4 | 3 | 2 | 1 | 5 | 64.28   | 92.84  | 8.94  |
| 25  | 5      | 5 | 4 | 3 | 2 | 1 | 62.33   | 93.34  | 8.48  |

consistent with the study of Chen et al. (2013). The effect values of Factor A (=0.91), D (=0.88), and F (=0.85) are close to each other, implying that their influences on co-gasification are almost equivalent. The effect value of Factor E (=0.56) is the lowest among the six factors. This highlights the insignificant role played by the S/F ratio on co-gasification.

### 3.2. Optimum co-gasification

The maximum mean S/N ratio of Factor A is 10.42 and is exhibited at Level 1 (Fig. 2a). This suggests that the fuel blend with BBR = 5 wt% gives a better performance than the other BBRs. The combination of Factor A and Level 1 is denoted by A1. In regards to Factor B, Level 2 with the O/F ratio of 0.7 leads to the highest performance of co-gasification (mean S/N ratio = 12.83); hence the recommended combination of Factor B is B2. The combination of Factor C and Level 4, namely, C4 (10.75), is also suggested. This reveals that eucalyptus torrefied at 300 °C is a better fuel for blending with coal as feedstock. Corresponding to Factors D, E, and F, their combinations should be D2 (10.39), E3 (10.26), and F1 (10.44), respectively. This implies that operation at a gasification pressure of 2 MPa, S/F ratio of 7%, and inlet temperature of 27 °C is suggested. Accordingly, the operating conditions from the combination of A1, B2, C4, D2, E3, and F1 are referred to as the optimum operation for the co-gasification of biomass and coal.

**Fig. 2.** Profiles of (a) mean S/N ratio and (b) factor effect value.

The aforementioned combination is presumed to be the optimized operation of co-gasification resulting from gathering the maximum mean S/N ratios of the six factors. But this combination is not included in the  $L_{25} (5^6)$  orthogonal array (Table 3). To verify the optimum co-gasification of the recommended operation, six different cases are tested and compared with each other. Details of the six cases are tabulated in Table 4. In brief, all factors with

Level 1 are selected as Case 1; all factors with Level 2 are combined together in Case 2, and so forth, for Cases 3–5. The recommended operation, namely, the combination of A1, B2, C4, D2, E3, and F1, is assigned as Case 6. The predicted values of CGE and CC are demonstrated in Fig. 3a, while the obtained S/N ratios are plotted in Fig. 3b. The values of CGE for Cases 1–5 are 61.72%, 78.92%, 72.40%, 67.67%, and 62.43%, respectively. The value of CGE for the optimum case is 80.99%, which is higher than Cases 1–5. Corresponding to the six cases, the values of S/N ratios are 8.34, 13.52, 11.18, 9.81, 8.54 and 14.42, respectively; and, as can be seen, the value of the S/N ratio of the optimum case is higher than those of the other five cases. The foregoing value is also higher than the value of Run 2 (=14.08), where the latter is the maximum value in the 25 runs (Table 3). Consequently, this verifies that the recommended combination from the Taguchi method provides the optimum operation for the co-gasification of torrefied biomass and coal. Of the six cases, the co-gasification performance of Case 1 is lower than the others. This can be explained by it having the lowest O/F ratio among the cases. This is also the reason why the CC value of Case 1 is by far the smallest. The decline in the values of CGE for Cases 2–5 is due to the trend of chemical reactions toward fuel combustion. By virtue of more CO<sub>2</sub> rather than CO formation when the test switches from Case 2 to Case 5, it is noted that the value of CC is always higher than 80%.

The concentration (mole fraction) profiles of CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O and syngas (i.e. CO+H<sub>2</sub>) in the product gas of the six cases are shown in Fig. 4. Case 1 has the lowest BBR and the highest coal content (Table 2); therefore, its CO concentration is higher when compared to the other cases. It should be noted that the syngas concentration in Case 1 is high; however, the low CC value in this case implies that the total amount of syngas produced from co-gasification is low. The concentration of CO decreases from Cases 1–5, while the concentration of CO<sub>2</sub> has the opposite trend. The increased CO<sub>2</sub> concentration corresponds to the lowered CGE, as shown in Fig. 3a. More steam is blown into the gasifier in Case 5 (S/F = 0.15), which results in a higher H<sub>2</sub> concentration. Though the H<sub>2</sub> concentration in the optimum case is lower than that of Case 5, the former has a higher CO concentration. As a result, the CGE of the optimum case is higher than those of the other cases, as shown in Fig. 3a. Overall, the concentration of H<sub>2</sub>O is low, except for Case 3. This indicates that steam is sufficiently consumed for H<sub>2</sub> production in co-gasification.

### 3.3. Reaction phenomena

Fig. 5 demonstrates the isothermal contours in the gasifier under the six cases. In the earlier analysis, it was pointed out that the O/F ratio plays the most important role in co-gasification. The O/F ratio increases from Cases 1 to 5, thereby intensifying the exothermic oxidation reactions and leading to the fuel blend tending to be burned rather than gasified. This is the reason why the temperature at the exit of the gasifier has a trend to increase from Cases 1 to 5. As a result, the syngas concentration in the product gas is diminished (Fig. 4).

**Table 4**  
Level combination for co-gasification comparison of the six cases.

| Case    | Factor A | Factor B | Factor C | Factor D | Factor E | Factor F |
|---------|----------|----------|----------|----------|----------|----------|
| Level   |          |          |          |          |          |          |
| 1       | 1        | 1        | 1        | 1        | 1        | 1        |
| 2       | 2        | 2        | 2        | 2        | 2        | 2        |
| 3       | 3        | 3        | 3        | 3        | 3        | 3        |
| 4       | 4        | 4        | 4        | 4        | 4        | 4        |
| 5       | 5        | 5        | 5        | 5        | 5        | 5        |
| Optimum | 1        | 2        | 4        | 2        | 3        | 5        |

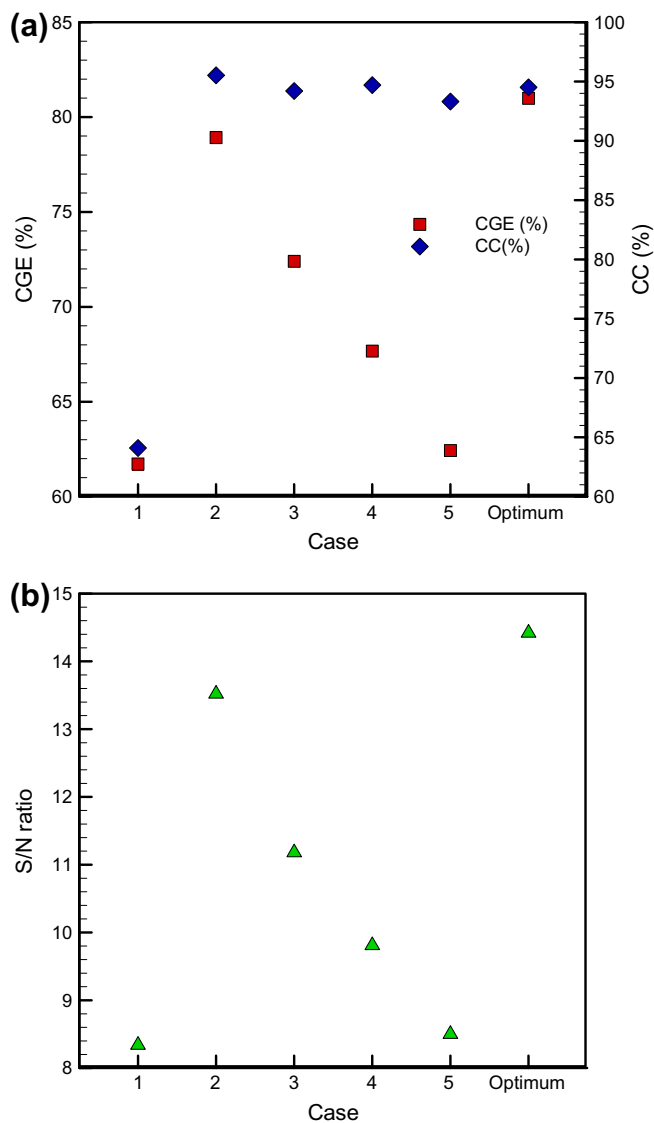


Fig. 3. Profiles of (a) CGE and CC and (b) S/N ratio.

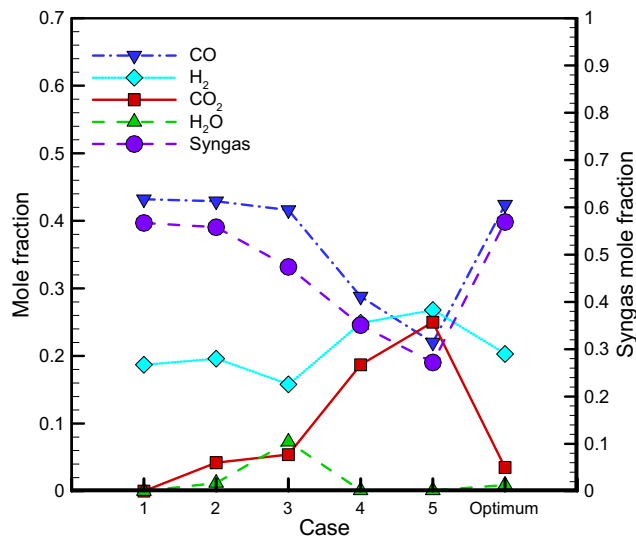


Fig. 4. Profiles of CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, and syngas concentrations in the product gas.

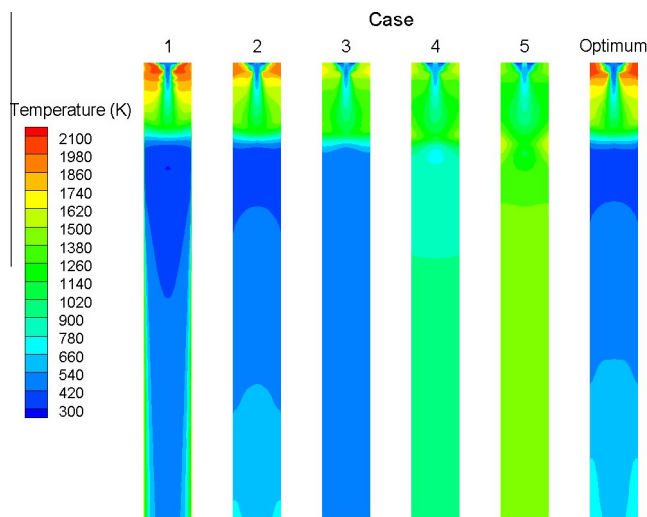


Fig. 5. Isothermal contours in the gasifier of the six cases.

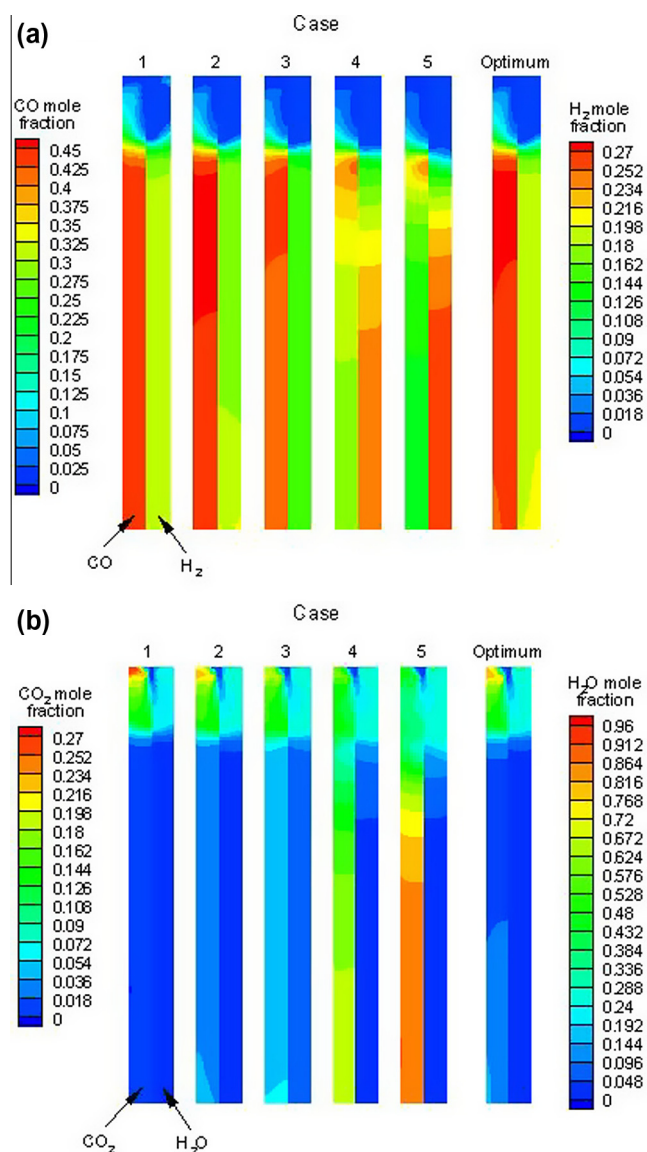


Fig. 6. Concentration contours of (a) CO and H<sub>2</sub> and (b) CO<sub>2</sub> and H<sub>2</sub>O in the gasifier at six cases.

Fig. 6a presents the concentration contours of CO and H<sub>2</sub> in the gasifier, while the concentration contours of CO<sub>2</sub> and H<sub>2</sub>O are shown in Fig. 6b. The concentrations of CO and H<sub>2</sub> in the vicinity of the gasifier entrance are very low, whereas the concentrations of CO<sub>2</sub> and H<sub>2</sub>O are relatively high as a consequence of fuel combustion. The concentrations of CO and H<sub>2</sub> progressively enlarge downstream, stemming from the reduction reactions of CO<sub>2</sub> and H<sub>2</sub>O with the fuel. The endothermic reduction reactions departing from the entrance result in a decrease of temperature in the gasifier (Fig. 5). The behavior of higher CO concentration accompanied by the lower temperature is consistent with the observation of Vicente et al. (2003). Unlike Cases 1–3, relatively more oxygen is supplied in Cases 4 and 5, and so the downstream CO<sub>2</sub> concentration is higher than the upstream one. The downstream H<sub>2</sub> concentration is always higher than the upstream, which is attributed to the reactions of steam with carbon (i.e. Eq. (10)) and CO (i.e. Eq. (13)). Overall, the isothermal and concentration contours of the optimum case are similar to those of Case 2 because their O/F ratios are the same, and this parameter is the most crucial factor in determining the performance of co-gasification.

#### 4. Conclusions

The Taguchi method has been employed to optimize the co-gasification of torrefied biomass and coal where a L<sub>25</sub> (5<sup>6</sup>) orthogonal array was established and the influences of six operating factors on the co-gasification were evaluated. The analyses of signal-to-noise ratios suggest that the influence strength order of each factor is: O/F ratio > biomass torrefaction temperature > biomass blending ratio > gasification pressure > inlet temperature > S/F ratio, and their better values for optimum operation are 5 wt%, 0.7, 300 °C, 2 MPa, 0.07, and 427 °C, respectively. The Taguchi method is a feasible tool for co-gasification optimization.

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